A Predictive Algorithm for Planning Observation of Transiting Exoplanets in Eclipsing Binary Stars

An Honors Thesis (HONRS 499)

By

Kenneth M. Moorhead

Thesis Advisor
Dr. Ron Kaitchuck

R. Kaitchuck
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Muncie, Indiana

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Abstract

The search for planets outside our solar system is vital for models of planetary formation. However, the relative size of a planet in comparison with its star and the difficulties created by line-of-sight geometry complicate detection, causing most information available to be a result of large sample wide field surveys. Based on reasonable assumptions of planetary formation, eclipsing binary stars are strong candidates for transit detection because they overcome the geometrical difficulties and also provide observers with a definite timeframe after which they may conclude that no planet of detectable size exists. Building upon the recent work of Ball State University master's program graduate Joe Childers that allowed our project to reach the conclusions mentioned prior, I have created a software algorithm that will determine when the most appropriate times for observation will occur so as to utilize telescope time more efficiently across multiple targets.

Acknowledgements

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- I would also like to thank my research partner, Garrison Turner. I cannot thank him enough for his companionship on many long nights of observations, collaboration on data reduction and analysis and especially his willingness to test the software that I have created.

Technological advancements in astronomical instrumentation have recently enabled astronomers to answer the ages-old question of whether the distant stars in the night sky had planets like those of our own solar system. As these exoplanets (extrasolar planets) were discovered, their surprising properties have given rise to even more questions about how planets form.

In 1992, the gravities of two planets orbiting pulsar PSR 1257+12 were found to be the source of periodic variations in the frequency of radio pulses (Wolszczan and Frail, 1992). A third planet was later discovered, and all three were determined to orbit within 0.5 AU of the pulsar – roughly the same orbital distance of Mercury. Discovering planets orbiting a neutron star formed from a supernova in such tight orbits was exceptionally surprising. However, most exoplanets that have since been discovered continue to display strange properties in unexpected locales (Childers, 2008).

Contemporary theories of planet formation were defied again with the first discovery of a planet orbiting 51 Pegasi, a main sequence star (Mayor and Queloz, 1995). The planet has a minimum mass of 0.468 times that of Jupiter, but surprisingly orbits its star in only 4.23 days. Theorists had held that gas giants could form only beyond the "frost line," the distance from the protostar where hydrogen compounds form ices. Explanations for "hot Jupiters" such as 51 Pegasi b have focused on mechanisms where the planet migrates in from the beyond the frost line to the tight orbits now commonly observed (Childers, 2008).

Typically, one of two methods is utilized in the search for exoplanets: measurement of radial velocity or measuring transits. The radial velocity measurements can yield only a minimum mass of a detected planet because the inclination of the orbit is unknown. However, transit studies can measure several attributes. The drop in light flux from the star as the planet transits can give the radius of the planet. The inclination that was previously unknown in radial velocity measurements can be determined from the light curve during transit. Combining this data with a Doppler spectroscopy radial velocity measurement will yield an accurate mass and density for the exoplanet. The ability of transiting planets to provide such detailed information makes them valuable to formation theorists (Childers, 2008).

Our fixed vantage point here on Earth allows us to view only a fraction of exoplanet transits. All planets will transit their star within that planet's orbital plane, however that plane must be somewhat aligned with the line of sight to Earth to allow for observation.

To work around the problems of orientations random to our line of sight, the choice of searching only in eclipsing binary stars lets us assume that the orbital plane is edge-on to Earth. The validity of this approach hinges on the assumption that planetary orbits will be coplanar with the two stars, but this assumption allows us to proceed with greater confidence that an exoplanet could transit from our perspective. Combined with the great number of bright binaries known, and their flat, featureless light curves when not in eclipse, we may conclude that eclipsing binary stars are good candidates for narrow-field photometry employing small telescopes (Childers, 2008).

The closed-system S-type orbits we have chosen to observe have stable orbit limits imposed by the gravity of each star in binary pair. The exoplanets we seek must be farther than its Roche limit from its parent star to avoid being shredded by tides, but the orbit must still be small enough that it will reside entirely within the parent star's Roche lobe. Kepler's law allows us to convert these orbital distances into orbital periods, and we can thusly determine a maximum period for a hypothetical planet in order to determine when sufficient observations have been made and that no planet of detectable size exists. These non-detections are valuable data for formation theorists developing models of planetary formation in binary systems, and could also contribute to models for the formation of the binary stars themselves.

In the summer of 2008, Dr. Ron Kaitchuck along with students Garrison Turner and I continued the study begun in 2006 with Masters student Joe Childers using the Ball State campus observatory. Joe had previously solved the problem of how long a system must be observed before declaring a null result and created software to aid in that determination. However, the diminishing returns in the coverage of possible transits that came along with repeated observations led to a desire to determine when during the course of an observation to target a given star for previously unseen observations. It is this desire to more efficiently use observation times that led to my senior research project and development of software that will aid future observers in planning the evening to be most effective.

Armed with the software developed by Childers, I set forth to deconstruct his algorithms and create a predictive formula that would allow us to efficiently schedule observation times. The Combined sheet of the Excel file we utilize is an array of binary digit flips that indicate whether a given phase of a particular possible period has yet been observed. The truth condition for each cell is determined by whether the duration of an observation includes captures the start and end times for a transit.

$$Start = \left(\frac{ObsStart - TransLength}{Period} - \left\lfloor \frac{ObsStart - TransLength}{Period} \right\rfloor \right) \times Period$$
$$End = \left(\frac{ObsEnd}{Period} - \left\lfloor \frac{ObsEnd}{Period} \right\rfloor \right) \times Period$$

(1)

Where ObsStart and ObsEnd are the respective start and end times for the observation session, TransLength is the duration of a transit based upon the size of the star, orbital distance and observational geometry, and Period is the orbital period of the planet about its star. The bracketed term on the right in each equation indicates the floor function. The difference enclosed in this equation is the *exact* equation for modulus division from discrete mathematics, yielding solely the remainder when dividing.

$$\frac{A}{B} - \left\lfloor \frac{A}{B} \right\rfloor = \text{A } \mathbf{mod} \text{ B}$$

(2)

The Start and End times are the remainders when dividing the *current date* by the period of the orbit. From the modulus equations above, the End time for a transit need simply me an integer multiple of the orbital period, and the Start is the End minus the length of the transit.

$$ObsEnd \equiv (n \times Period) + End$$
$$ObsStart \equiv ObsEnd - TransLength$$

(3)

By fast-forwarding through the orbits of the planet until we reach the present date, we can predict the end time of a hypothetical transit. This is the core of my scheduling software: rapidly cycling through multiples of each possible planetary period and adding the remainder of the End time for the planetary orbit. The equation is easily modified to target each ten-minute segment of each possible period as used by the software developed by Childers.

What my software will do is seek out each ten-minute window of each period that has not yet been observed, modify the End time accordingly by subtracting off ten-minute increments, and then cycle as described above to find the next time a particular phase of a period will occur.

Additional checks have been put in place to ensure the output times will always occur at night for the observatory to be used (SARA or BSU), and the list of occurrences for each phase-period combination is truncated for overlap of times. The user need only input the previous observation times as per Childer's instructions, the date for the next observation and the location of observatory to be used, and he will be returned with an observation window that primarily targets phases he has not yet observed!

The search for exoplanets is a valuable endeavor in aiding planetary formation theorists to build and refine their models that help explain our universe. Unfortunately, it is a process that relies largely on chance and observing large samples of stars to overcome the difficulties imposed by line-of-sight geometry. The decision to target eclipsing binary stars as candidates for exoplanet transits solves this problem based on reasonable assumptions, and also provides observers with a means to determine whether or not a planet of detectable size exists in the system. Developing a tool to help observers determine *when* to look at a given system is invaluable to these sometimes daunting efforts and will help surveys in completing their studies without wasting valuable telescope time.

Usage Instructions for the Observation Scheduler

(Steps 1-7 taken from Joe Childer's instructions for general use of the workbook)

1. Enter in the star's parameters on the Master worksheet.

2. Begin entering the Julian dates for the observations on Master worksheet.

3. The template starts with two observation worksheets, "Seen1" and "SeenLast." New worksheets are added by copying the "Seen1" worksheet.

4. Copy "Seen1" and place the copy before "SeenLast." The Combined sheet uses a worksheet range from "Seen1" to "SeenLast." Excel treats this as a range of tabs along the bottom of the window, so new "Seen" worksheets must be placed between these two to be included.

5. Rename the new worksheets to "Seen#" as appropriate. This number corresponds to the label on the Master worksheet assigned to the observation interval. This is purely aesthetics; all that matters for the spreadsheet to function correctly is that the new sheet's tab be between the sheets Seen1 and SeenLast.

6. Enter in this number in the upper left cell of the new observation worksheet. This action ***does*** carry a vital function.

7. The spreadsheet is in manual calculation mode, so that data entry is not slowed by the intensive calculations after each cell entry is typed. Press [F9] to calculate the spreadsheet.

8. With the workbook updated as per the steps above, click on the "Scheduler" sheet. Enter the Julian date for the next observation session and the observatory site where indicated.

9. Click the "Run Scheduler" button.

10. Times will be output in the cells indicated. There is a link on the sheet to convert from Julian date into the calendar date and HH:MM time.

11. For best results in planning a full evening session, paste the first begin and end times given back into the Master sheet, recalculate the workbook and run the scheduler again. This will ensure that the times output do not repeat again and will yield shorter windows in future runs.

12. Inevitably, the last few times given will *not* occur at night but rather during the day roughly one week from the observation date input. These are the times for phases that are not observable from either the SARA or BSU sites and are the result of stops implemented to keep the algorithm from looping infinitely and freezing the system.

References

Childers, Joseph M. A Search for Transiting Exoplanets in Eclipsing Binary Stars.

Mayor, M. and Queloz, D. 1995, *Nature,* **378,** 355-359

Wolszczan, A. and Frail, D.A. 1992, *Nature*, **355**, 145-147